Available online at www.sciencedirect.com

ScienceDirect

Structural Integrity Procedia 00 (2019) 000–000

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

1st Virtual Conference on Structural Integrity – VCSI1

Structural integrity assessment of pressure equipment by Acoustic Emission and data fractal analysis

Stefano Porziani[a,*], Giuseppe Augugliaro[b], Fabio Brini[b], Carlo Brutti[a], Andrea Chiappa[a], Corrado Groth[a], Canio Mennuti[b], Paolo Quaresima[b], Pietro Salvini[a], Alessandro Zanini[a], Marco Evangelos Biancolini[a]

[a] *University of Rome "Tor Vergata", Dept. Enterprise Engineering, Via del Politecnico 1, Rome 00133, Italy*
[b] *INAIL, Department of Technologic Innovation, via Roberto Ferruzzi 38/40, Rome 00143, Italy*

Abstract

Fractal analysis appears to be a relevant tool toward the interpretation of acoustic emissions signals related to the stress and damage of the material and this paper shows how it can be adopted for health monitoring of various structures. The fractal dimension quantifies the order/disorder of the signals and is correlated to the applied stress/pressure and loading cycles. The chart of such evolution allows to evaluate nucleation and propagation of a fatigue crack and to understand the margin of safety of the investigated structure in a specific moment of its life. Fractal analysis of EA signals can be combined with other experimental and theoretical techniques to accurately foresee the damage accumulated and the residual life. In this study we have investigated three pressure tanks at known state of ageing and observed a good agreement with other well-stated methods based on acoustic emissions.

Keywords: Acoustic Emission; Fractal Analysis; Pressure Equipment; Integrity Assessment.

---

1. Introduction

With the term Acoustic Emission (AE) scientists and engineers identify the phenomena for which elastic waves, generated from a change internal to its structure, are emitted by a material. These waves can be originated from deformation, dislocation motion, crack initiation or propagation under both static and fatigue loading conditions (Davis (1989)). The AE have attracted interest in Non Destructive (ND) controls applications thanks to the fact that they are generated by defects and their progression. AE are thus classified as Non Destructive Method for Structural Health Monitoring, gaining a relevant position both in the investigation (Davis (1989)) and in engineering practice (Rogers (2001), Hamstad (1986)). Techniques based on Acoustic Emission Monitoring can successfully not only catch the

---

[*] Corresponding author.
E-mail address: g.augugliaro@inail.it

damage occurring, but also defect location and its growth rate. This technique allow to decide if a maintenance intervention is sufficient or if the equipment has to be put in the out-of-service state. AE based methods are currently successfully used in several structural damage detection application, such as: deformation and damaging of materials (Biancolini et al. (2007)), fracture mechanics (Huang et al. (1998), Berkovits and Fang (1995)) , composite materials (Hamstad (2000)), concrete (Ohtsu (2015)) and rock mechanics (Manthei et al. (2000), Gregori et al. (2005)), fatigue of metals (Hamel et al. (1981), Lee et al. (1996), Biancolini et al. (2006)), life assessment of mechanical components (Mba (2002), Augugliaro et al. (2013a), Rauscher (2005)) and corrosion monitoring (Pollock (1986)).

When analysed, signal from EA can furnish two kind of information. EA signal is proportional to stress acting on structure and analysing it to obtain this kind of information (stress intensity) it was possible to define several analysis techniques, such as the study of the energy of each individual event, the cumulated energy and the number of counts (Augugliaro et al. (2013a), Augugliaro et al. (2013b)).

The second kind of information that a EA signal can furnish is related with the fatigue phenomenon, where the accumulation of damage due to cyclic loading originates a specific sequence of acoustic events during time (Paparo and Gregori (2003)). The mathematical tool that can successfully manage and display such a complex signal (Barnsley et al. (1988), Peitgen et al. (2006), Vinogradov et al. (2014)) is the fractal analysis. Mandelbrot (Mandelbrot (1983)) demonstrated that fractals have many features in commons with irregular structures present in natural environment and phenomena. Taking as example the Self-Similarity problem, fractals can describe in the same manner both cauliflower shape and sea eroded coast or, moreover, the pattern of vibrating signal generated by micro-seismic ground activity. Fractals, thanks to this particular characteristic, are used by researches to describe physical events (Peitgen et al. (2006)).

In this paper, the authors will show the fractal approach in analysing AE signals in the engineering field of pressure vessels ND structural monitoring. Even if AE use in the pressure vessel study is already present in available scientific literature (see for example (Rauscher (2005)), fractal analysis application is a relatively new topic (Biancolini et al. (2019)). The widespread of this novel application will increase the number of techniques available to assess the damaging process of material (Augugliaro et al. (2013a), Augugliaro et al. (2013b)) and to support the established traditional methods (Mandelbrot (1983), EN (2002), De Petris et al. (2004)).

2. Fractal analysis – box counting method

The fractal approach to AE analysis adopted in this work is the Box-Counting Method (BCM). BCM allows to evaluate the fractal dimension of any signal scattered in a time interval under exam. Applying BCM to a AE signal, it is possible to assess signal and moreover to rate the emission of loaded structures. If a time-discrete signal is given (Turcotte (1997)), it is possible to define a time interval μ, called 'ruler', so that the whole temporal window can be divided into an integer number of rulers, which do not superimpose. Considering Fig. 1, a '+1' quantity is added to the counter $G(\mu)$ if a ruler μ contains at least one data above a specified threshold value. Plotting the $G(\mu)$ counter versus μ in a log–log graph, called Richardson's diagram (Fig. 2), it is possible to define the slopeh $H = tg\phi$, which is equal to the fractal dimension changed in sign ($Dt = -H$)

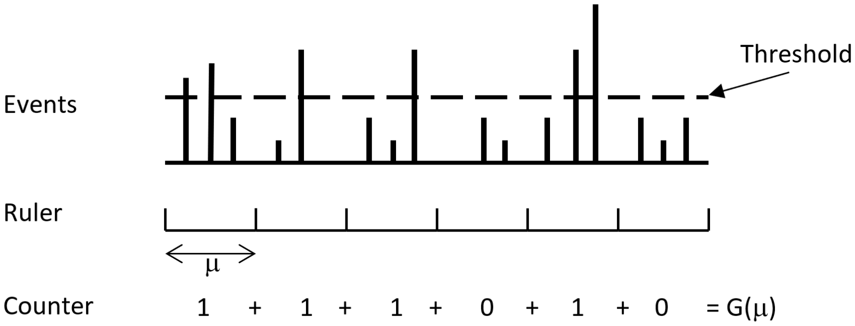


Fig. 1. Box-counting method.

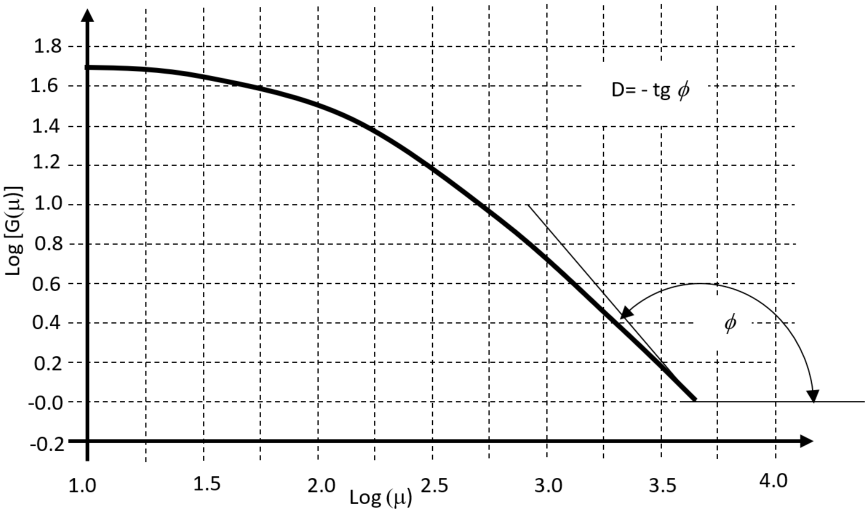


Fig. 2. Richardson's diagram

In (Paparo and Gregori (2003)) and in (Gregori et al. (2005))) authors distinguished between AE source in a 3D and in a 2D space distribution, demonstrating the effectiveness of the fractal dimension based method in analysing AE sources.

A 3D spatial distribution of AE can, for example, occurs if a fluid at high temperature and at high pressure penetrates solid pores, causing the crystal lattice to breack. AE events for this 3D spatial distribution case, appears to have no correlation, since the random nature of the first cause of tension (i.e. the fluid penetrating pores) and no AE source can remember if other sources already reached a critical condition.

In the case of a 2D AE sources, as, for example, the breaking of a crystal along a fracture plane, the emissions are more correlated. In fact, the fracture is more likely to occur near an already cracked zone, and the new AE event hold memory of the closest bond which collapsed along the preferential fracture plane.

BCM, which can be applied with no effort to AE time series, results to be a reliable mean to assess the different behaviour of AE events, and in particular for the case of nucleation and propagation of defects. If applied to a 3D case, in which the sources are not correlated, the fractal dimension D is equal to 1, since the system has a completely disordered pattern of sources. When the sources become more organised and located along a fracture plane, D decreases until reaching the value of 0, with the emitting defects located in a limited area which is near to the collapse. This approach has been applied to maraging steel blades of the VIRGO gravitational antenna (Braccini et al. (2002)), which were intensively tested under bending load conditions. By means of two narrow-band piezoelectric sensors of resonant frequency of $25kHz$ and $200kHz$, the dislocation movement and Kaiser effect were studied: the fractal dimension decreased progressively from value near 1 to values near 0, which correspond respectively to disordered pattern of emitting defects and ordered AE sources.

Fractal dimension calculation by BCM has also been applied to the study of nucleation and growth of fatigue cracks in steel specimen under rotating bending loading condition (Biancolini et al. (2006)). This study confirmed that, as observed by others (Berkovits and Fang (1995), the fractal dimension D decreases approaching the collapse of the structure monitored, but also showed a relationship between the counts of a AE event and the stress-intensity factor ΔK.

3. Control of underground tank by the EA

The ND method currently used to periodically verify GPL tank status is depicted in Fig. 3.

The detailed procedure can be found in (De Petris et al. (2004)), the fundamental features of the technique are summarized in the following:

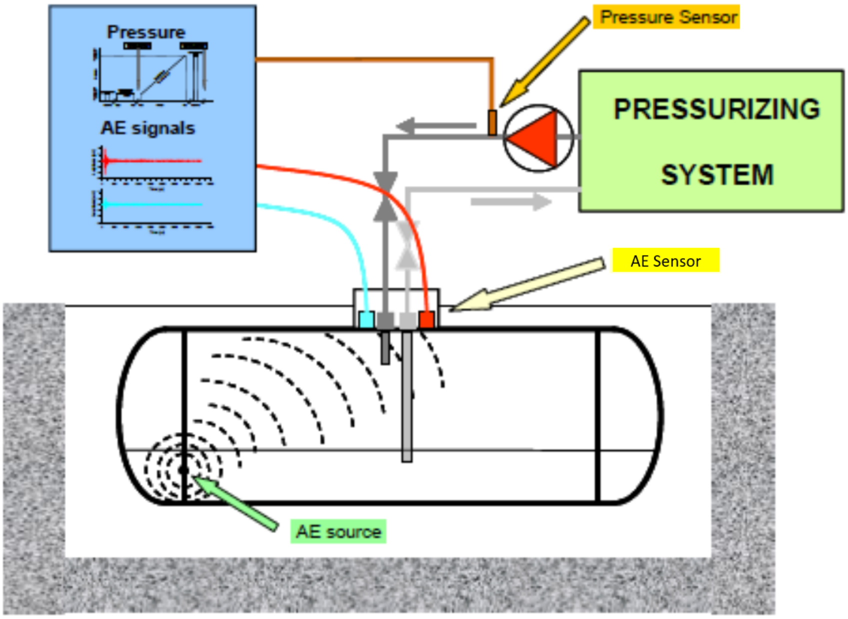


Fig. 3. ISPESL/INAIL AE procedure

- During the test, vessel has to be pressurezed up to the maximum value of $16 bar$ with a gradient of $0.2 \pm 0.05 bar/min$;
- AE data registered by the pair of AE channels (red and cyan in Fig. 3) have to be analysed to extract relevant information for structural integrity assessment of the tank;
- a synthetic indicator γ can be evaluated from AE data using an INAIL developed algorithm;
- the synthetic indicator γ takes into account both quantitative and qualitative parameters of the AE;
- the quantitative main parameter is the overall intensity in the form of AE and can be correlated to the total number of hit count (HC). The second quantitative parameter taken into account by γ evaluation algorithm is the overall detected energy (EC). The EC parameter is employed to evaluate the relevance (or magnitude) of the AE event sequence related to the physical phenomenon. The EC is also used to compare the status of different monitored tanks;
- the extracted parameters are also used to perform a qualitative analysis, providing thus information about the evolution of the acoustic activity. It is easy to understand that high counts number and high emitted energy levels are a clear sign of a critical material status. But the level of critical issues depends also on the way in which events occurs: if the same amount of energy is released on a wider range the tank is in a less dangerous condition; moreover, if the energy release is regular during the testing time interval, it can be stated that the tank is in a stationary condition with a low risk level. On the other hand, if the testing procedure register a highly irregular energy release, or sudden energy levels change, it is possible to state that the monitored tank is reaching a critical state.

The illustrated procedure proven to be capable to take into account both the quantitative and qualitative parameters describing the physical phenomenon, and can be used to define two parameters:

- $ICSE$ = Criticalyty Index for Business Stability;
- $ISRE$ = Energy Release Historical Index.

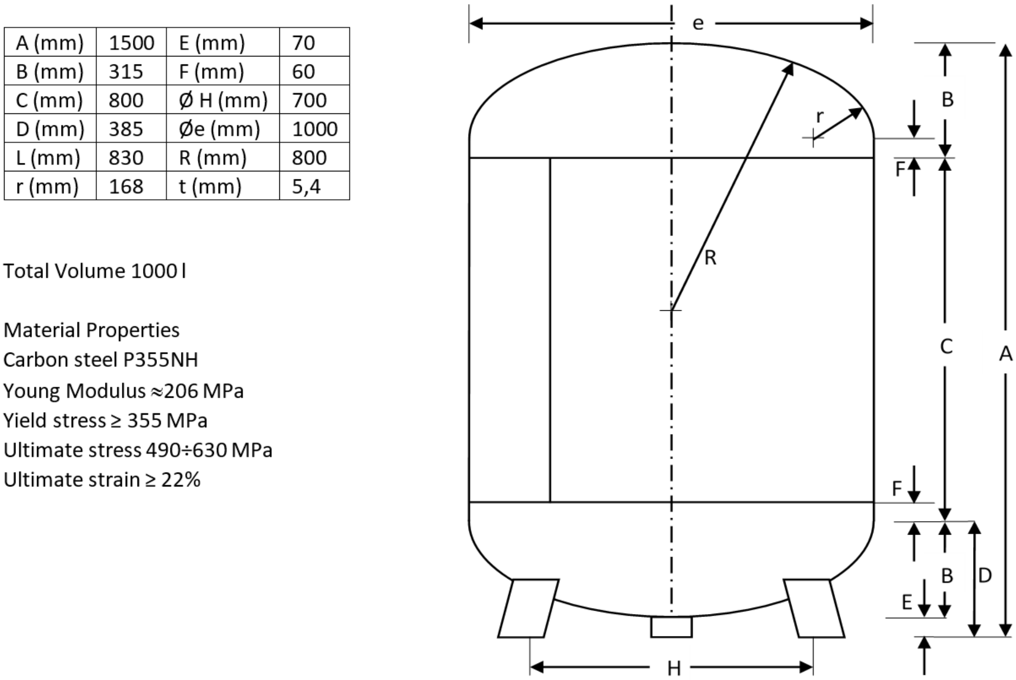
These two parameters are constantly updated during the testing of underground tanks. Moreover these two parameters are summarized into the synthetic indicator $\gamma = f(ICSE, ISRE)$. The mathematics behind the γ evaluation algorithm are beyond of the scope of this paper and is currently patented by Italian National Authority for Patents at the Ministry of Economic Development (March 2009). The γ parameter allows to classify the tanks according to two structural risk levels:

CLASS 1: Vessels for which a non-significant level of AE activity has been registered. This class levels can continue their mission for an additional period according to the country legislation (10 years according to Italian regulations)

CLASS 2: Vessels for which a significant AE activity is registered. For vessels that are this class during the test one of the following criteria has to be met: $\gamma_{max} > 0.95$, or more than $N_1 = 30hits$ with amplitude $A_1 > 75dB$, or more than $N_2 = 15hits$ with amplitude $A_2 > 85dB$ or more than $N_3 = 1500hits$ with amplitude $A_3 > 40dB$. These vessels cannot be maintained in services and have to be dismissed.

4. Analysis of underground tanks using EA and fractal analysis

As a consequence of outcomes of studies reviewed in section 2, AE analysis by means of fractal mathematics is a non-destructive monitoring methodology that has great potential. The BCM technique, in particular, has been applied to AE test performed on LPG tanks and compared with the procedure outlined in section 3, with the objective to verify results predicted by both methods (BCM and ISPESL/INAIL procedure) in term of collapse risk. The vessel typology and its geometrical and mechanical characteristics are summarized in Fig. 4



A (mm)	1500	E (mm)	70
B (mm)	315	F (mm)	60
C (mm)	800	Ø H (mm)	700
D (mm)	385	Øe (mm)	1000
L (mm)	830	R (mm)	800
r (mm)	168	t (mm)	5,4

Total Volume 1000 l

Material Properties
Carbon steel P355NH
Young Modulus ≈206 MPa
Yield stress ≥ 355 MPa
Ultimate stress 490÷630 MPa
Ultimate strain ≥ 22%

Fig. 4. Underground vessels tested

Three different underground vessels with same characteristics were tested and analysed using the ISPESL/INAIL (see Fig. 3 procedure to extract tank parameter γ: only the firts two vessels passed the testing procedure, whilst the third one did not successfully passed the check.

Results obtained analysing vessel 1 and vessel 2 are depicted in Fig. 5: the value of fractal dimension D_t remains practically constant during all pressurization process. This means that AE sources distribution did not change during the test and did not evolved through a more organized, and dangerous, one. Thus, there is not in the two tested vessels an area of possible critical condition.

In Fig. 5 are also visible evolution of parameter γ values during the pressurization. Since for first two tested vessels it results that $\gamma < \gamma_{lim}$, where γ_{lim} was assumed equal to 0.95, also according to the observation of this parameters both underground vessels passed the non-destructive monitoring test.

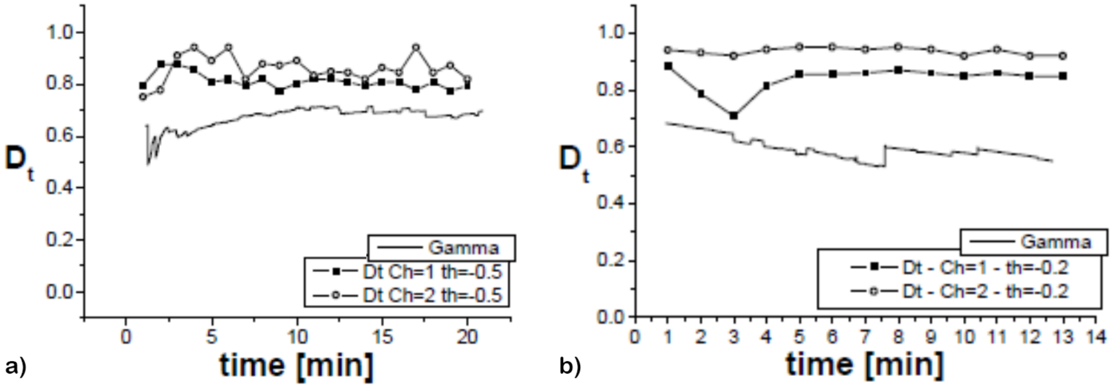


Fig. 5. Result of AE tests for vessel 1 and vessel 2

In the case of the third vessel, results are depicted in Fig. 6. In the test period comprise between the 15^{th} and the 25^{th} minute, test parameter γ reaches the lower limit. In the same time interval, fractal dimension decreases from values near 0.9 to 0.3. This last value clearly shows that AE is generated by a restricted number of sources, more organized and thus indicating a relevant damaging process. In this condition the vessel cannot operate in a safe way. On the other hand, during the test, no macroscopic failure on the vessel was observed, since no gas leak occurred. The fractal dimension value, which after decreasing to the value of 0.3 reaches again to a near unity value, gives the information that the material has residual strength to bear the pressure applied, even if a damaging process is still active. The external load applied, the testing pressure, generated a local loss of strength, but, given the low level of stress applied, the vessel material doesn't reach the incipient breaking condition, even if the damage is irreversible. If the pressure loading increases, the damage will increase and a the same time the fractal dimension will decrease up to the collapse.

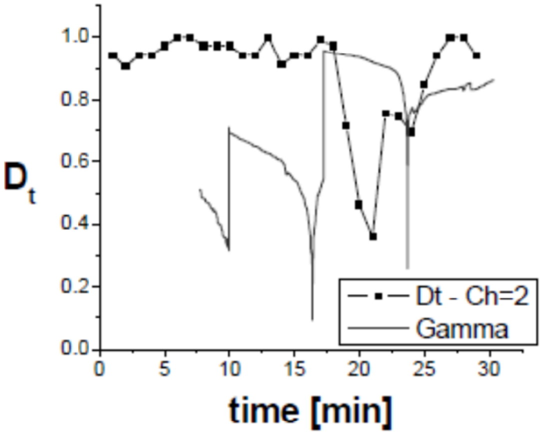


Fig. 6. Result of AE tests for vessel 3

5. Conclusions

AE signal analysis by means of BCM fractal approach can be successfully applied in non-destructive monitoring of structures, as clearly evidenced by literature investigated. This technique allows to gather information about on structure damage both in the static and dynamic loading case. D_t, the fractal dimension, as defined in previous sections, can measure the disorder of AE sources, evidencing if a particular local damaging process is active and giving information about its evolution under static and dynamic loading. A sudden decrease of D_t, tells technicians and engineers that in a portion of tested material there is a concentration of AE events: it is then possible to monitor this damaged zone from nucleation of defect through its growth, until structure collapse.

In this work, the application of this method to the evaluation of structural risk of underground LPG vessels is investigated. This particular kind of vessels is regularly tested using the ISPESL/INAIL procedure, which analyses the AE signal during a pressurization cycle. Three different vessels were analysed adopting both the fractal analysis by means of BCM and the ISPESL/INAIL procedure. According to both approach adopted, one of this vessels could not continue to operate in safety condition, since, at the same time interval, D_t value registered a sudden variation and decrease, whilst γ parameter decreased under the limit value of 0.95. This led to the conclusion that both procedure are in good agreement.

In spite of the encouraging results obtained, a deeper understanding of D_t during the defect growth is necessary. The topics on which further investigations can be carried out could be, as example:

- the existence of a limit for D_t that can be used to differentiate between safety emission condition and critical one, analogous to γ_{lim} in the ISPESL/INAIL procedure;
- if the D_t limit is dependent or not on the material, type, loading type and crack origin (stress concentration, corrosion, plastic zone, etc.).

6. Acknowledgements

The present work is developed within the research project ”SMART MAINTENANCE OF INDUSTRIAL PLANTS AND CIVIL STRUCTURES BY 4.0 MONITORING TECHNOLOGIES AND PROGNOSTIC APPROACHES - MAC4PRO ”, sponsored by the call BRIC-2018 of the National Institute for Insurance against Accidents at Work - INAIL.

References

Augugliaro, G., Brini, F., Brutti, C., Lazzaro, D., 2013a. Parametri di emissione acustica per la valutazione del processo di danneggiamento strutturale. XV AIPnD, Trieste ISBN:978-88-89758-14-4.

Augugliaro, G., Brini, F., Lazzaro, D., Mennuti, C., Quaresima, P., 2013b. A.E. parameters to evaluate damaging process in structures. VIII E-GLEA , Buenos Aires .

Barnsley, M.F., Devaney, R.L., Mandelbrot, B.B., Peitgen, H.O., Saupe, D., Voss, R.F., Fisher, Y., McGuire, M., 1988. The science of fractal images. Springer.

Berkovits, A., Fang, D., 1995. Study of fatigue crack characteristics by acoustic emission. Engineering Fracture Mechanics 51, 401–416.

Biancolini, M., Brutti, C., Paparo, G., Zanini, A., 2006. Fatigue cracks nucleation on steel, acoustic emission and fractal analysis. International Journal of Fatigue 28, 1820–1825.

Biancolini, M., Brutti, C., Paparo, G., Zanini, A., 2007. Acoustic emission monitoring of damage evolution in mechanical materials. Convegno E-GLEA Oberà, Argentina .

Biancolini, M., Brutti, C., Zanini, A., Salvini, P., 2019. Acoustic emission data fractal analysis for structural integrity assessment of pressure equipment, in: 1st EPERC International Conference Pressure Equipment Inovation and Safety.

Braccini, S., Casciano, C., Cordero, F., Frasconi, F., Gregori, G., Majorana, E., Paparo, G., Passaquieti, R., Puppo, P., Rapagnani, P., et al., 2002. Monitoring the acoustic emission of the blades of the mirror suspension for a gravitational wave interferometer. Physics Letters A 301, 389–397.

Davis, J.R., 1989. ASM Handbook: Nondestructive evaluation and quality control. volume 17. ASM International.

De Petris, C., Delle Site, C., Lenzuni, P., Mazzocchi, V., Mennuti, C., 2004. An innovative ae technique for the verification of underground and buried pressure equipment, in: 12 th International Conference on Experimental Mechanics”–Bari.

EN, 2002. EN 12818:2002, LPG equipment and accessories. inspection and requalification of LPG tanks up to and including 13 m^3 underground – superseded by EN 12817:2010.

Gregori, G.P., Paparo, G., Poscolieri, M., Zanini, A., 2005. Acoustic emission and released seismic energy. Natural Hazards and Earth System Science 5, 777–782.

Hamel, F., Bailon, J., Bassim, M., 1981. Acoustic emission mechanisms during high-cycle fatigue. Engineering Fracture Mechanics 14, 853–860.

Hamstad, M., 2000. Thirty years of advances and some remaining challenges in the application of acoustic emission to composite materials. Acoustic Emission beyond the Millennium; Kishi, T., Ohtsu, M., Yuyama, S., Eds , 77–91.

Hamstad, M.A., 1986. A review: acoustic emission, a tool for composite-materials studies. Experimental Mechanics 26, 7–13.

Huang, M., Jiang, L., Liaw, P.K., Brooks, C.R., Seeley, R., Klarstrom, D.L., 1998. Using acoustic emission in fatigue and fracture materials research. JOM 50, 1–14.

Lee, C., Park, C., Chang, Y., 1996. Precise determination of fatigue crack closure in al alloys. Materials Science and Engineering: A 216, 131–138.

Mandelbrot, B.B., 1983. The fractal geometry of nature. volume 173. WH freeman New York.

Manthei, G., Eisenblätter, J., Spies, T., 2000. Acoustic emission in rock mechanics studies.

Mba, D., 2002. Applicability of acoustic emissions to monitoring the mechanical integrity of bolted structures in low speed rotating machinery: case study. Ndt & e International 35, 293–300.

Ohtsu, M., 2015. Acoustic emission and related non-destructive evaluation techniques in the fracture mechanics of concrete: fundamentals and applications. Woodhead Publishing.

Paparo, G., Gregori, G.P., 2003. Multifrequency acoustic emissions (ae) for monitoring the time evolution of microprocesses within solids, in: AIP Conference Proceedings, AIP. pp. 1423–1430.

Peitgen, H.O., Jürgens, H., Saupe, D., 2006. Chaos and fractals: new frontiers of science. Springer Science & Business Media.

Pollock, A.A., 1986. Acoustic emission capabilities and applications in monitoring corrosion, in: Corrosion Monitoring in Industrial Plants Using Nondestructive Testing and Electrochemical Methods. ASTM International.

Rauscher, F., 2005. Pressure Test and Acoustic Emission Examination. Shaker.

Rogers, L., 2001. Structural and engineering monitoring by acoustic emission methods–fundamentals and applications. Lloyd's Register Technical Investigation Department .

Turcotte, D.L., 1997. Fractals and chaos in geology and geophysics. Cambridge university press.

Vinogradov, A., Yasnikov, I.S., Estrin, Y., 2014. Stochastic dislocation kinetics and fractal structures in deforming metals probed by acoustic emission and surface topography measurements. Journal of Applied Physics 115, 233506.